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original research

Shoulder External Rotation Fatigue and Scapular Muscle Activation and Kinematics in Overhead Athletes

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Context: Glenohumeral external rotation (GH ER) muscle fatigue might contribute to shoulder injuries in overhead athletes. Few researchers have examined the effect of such fatigue on scapular kinematics and muscle activation during a functional movement pattern.

Objective: To examine the effects of GH ER muscle fatigue on upper trapezius, lower trapezius, serratus anterior, and infraspinatus muscle activation and to examine scapular kinematics during a diagonal movement task in overhead athletes.

Setting: Human performance research laboratory.

Design: Descriptive laboratory study.

Patients or Other Participants: Our study included 25 overhead athletes (15 men, 10 women; age = 20 ± 2 years, height = 180 ± 11 cm, mass = 80 ± 11 kg) without a history of shoulder pain on the dominant side.

Intervention(s): We tested the healthy, dominant shoulder through a diagonal movement task before and after a fatiguing exercise involving low-resistance, high-repetition, prone GH ER from 0° to 75° with the shoulder in 90° of abduction.

Main Outcome Measure(s): Surface electromyography was used to measure muscle activity for the upper trapezius, lower trapezius, serratus anterior, and infraspinatus. An electromyographic motion analysis system was used to assess 3-dimensional scapular kinematics. Repeated-measures analyses of variance (phase × condition) were used to test for differences.

Results: We found a decrease in ascending-phase and descending-phase lower trapezius activity ($F_{1,25} = 5.098$, $P = .03$) and an increase in descending-phase infraspinatus activity ($F_{1,25} = 5.534$, $P = .03$) after the fatigue protocol. We also found an increase in scapular upward rotation ($F_{1,24} = 3.7$, $P = .04$) postfatigue.

Conclusions: The GH ER muscle fatigue protocol used in this study caused decreased lower trapezius and increased infraspinatus activation concurrent with increased scapular upward rotation range of motion during the functional task. This highlights the interdependence of scapular and glenohumeral force couples. Fatigue-induced alterations in the lower trapezius might predispose the infraspinatus to injury through chronically increased activation.

Key Words: muscle function, rotator cuff, upper extremity

Key Points

- Shoulder external rotation muscle fatigue contributed to altered scapular muscle activation and kinematics.
- From prefatigue to postfatigue, lower trapezius activation decreased by 4%, infraspinatus activity increased in the descending phase by 4%, and scapular upward rotation motion increased in the ascending phase by 3°.
- Upper trapezius and serratus activation did not change from prefatigue to postfatigue.
- The force couple between the lower trapezius and infraspinatus was interdependent, and alterations in the lower trapezius due to shoulder external rotation muscle fatigue might predispose the shoulder to injury.

Shoulder injuries are common in overhead athletes, with as many as 44% experiencing shoulder problems and 29% having shoulder pain at some point in their careers.[1] The high prevalence and incidence of shoulder pain in these athletes are attributed largely to repetitive and excessive stress placed on the shoulder during overhead sports. Such repeated motion is thought to create muscle fatigue, thereby increasing the risk of shoulder injury by altering muscle activation patterns, force couples, and kinematics in the shoulder girdle.[2–6]

Using external rotation fatigue protocols aimed at the rotator cuff muscles, investigators have demonstrated concurrent decreases in scapular posterior tilt and external rotation together with increased clavicular retraction.[3,6] However, researchers have reported conflicting results of alterations in upward rotation, with some showing decreased scapular upward rotation[5,6] and others showing increased upward rotation.[3,4] A delay in middle and lower trapezius activation has been seen in participants with symptoms of subacromial impingement compared with those without such symptoms.[7] Other investigators[8–13] have studied alterations in shoulder range of motion (ROM), torque, and static joint position sense after simulated pitching sessions. However, to our knowledge, none of them simultaneously assessed fatigue-induced electromyographic (EMG) changes in specific periscapular or rotator cuff muscles and their effects on 3-dimensional scapular kinematics through a functional movement pattern in overhead athletes. We believe this is important to understanding the relationship between the changes in scapular position seen and measures of muscle activity. Therefore, the purpose of our study was to investigate the effects of glenohumeral external rotation (GH ER) muscle fatigue in 90° of abduction on upper trapezius, lower trapezius, serratus anterior, and infraspinatus muscle activation and on scapular kinematics during a diagonal movement task in overhead athletes. We hypothesized that repeated GH ER in 90° of abduction would result in infraspinatus fatigue. This fatigue would cause a compensatory increase in the activity of the upper trapezius, lower trapezius, and serratus anterior, thereby creating an unstable scapular base.

METHODS

Data were collected in a single session lasting approximately 90 minutes. We used a single-group, pretest-posttest measurement design.

Participants

Twenty-five people (15 men, 10 women; age = 20 ± 2 years, height = 180 ± 11 cm, mass = 80 ± 11 kg) who were involved in physical activities requiring repeated arm motion above shoulder level for a minimum of 30 minutes per session at least 3 times per week volunteered to participate in the study. All participants were competing in an overhead sport at the collegiate club or intercollegiate level. Six participants were baseball players, 4 were tennis players, 12 were volleyball players, and 3 were swimmers. Twenty-three participants were right-hand dominant, and 2 were left-hand dominant. Testing was performed on the *dominant arm*, which was defined as the arm used to throw a ball for maximal distance.

Volunteers were excluded from the study if they had a history of major shoulder injury (eg, shoulder instability, rotator cuff tendinopathy) or surgery. They also were excluded if they reported experiencing shoulder pain, were taking medications for shoulder pain, or had participated in rehabilitation for shoulder pain in the 6 months before the study.

They were instructed not to participate in any activities (pitching, throwing, serving, spiking, upper body workout) that might fatigue the shoulder muscles for at least 12 hours before testing. Participants provided written informed consent, and the study was approved by the University of North Carolina Biomedical Institutional Review Board.

Instrumentation

We studied fatigue-induced alterations in the upper trapezius, lower trapezius, and serratus anterior muscles because of their role in scapular positioning.[2] The infraspinatus was chosen because it seems to show the greatest change in activation with repeated elevation and external rotation tasks.[3,6] Activation amplitude of these muscles was measured using a telemetry surface EMG system (model T42L-8T0 Telemetry; Konigsberg Instruments, Inc, Pasadena, CA). The system consists of an 8-channel differential preamplifier-encoder-transmitter and a receiver-demodulator (input impedance = 200 kΩ, common mode rejection ratio > 70 dB, signal-to-noise ratio > 40 dB). The EMG signal was amplified by a factor of 10000 over a bandwidth of 0.01 to 2000 Hz and passed via an analog-to-digital converter (National Instruments Corporation, Austin, TX), which sampled EMG signals at 1000 Hz, to a storage computer. Bipolar silver chloride surface electrodes (Medicotest, Rolling Meadows, IL) were used. The electrode diameters were 10 mm, with a center-to-center interelectrode distance of 2.0 cm.

Three-dimensional shoulder kinematics were assessed using a Flock of Birds (Ascension Technology Corporation, Burlington, VT) electromagnetic motion analysis system controlled by The MotionMonitor (Innovative Sports Training, Inc, Chicago, IL) software at a sampling rate of 50 Hz. Three electromagnetic tracking sensors were attached with double-sided tape to the thorax over the spinous process of T3, the dominant shoulder over the broad flat surface of the scapular acromion process, and the distal one-third of the posterior upper extremity, with the sensor over the area of least muscle mass to minimize potential sensor movement (Figure 1). To assess shoulder kinematics, we digitized bony landmarks to develop local coordinate systems. The sensor coordinate systems then were converted to anatomically relevant axes following the recommendations of the International Shoulder Group.[14] We also followed these guidelines to convert

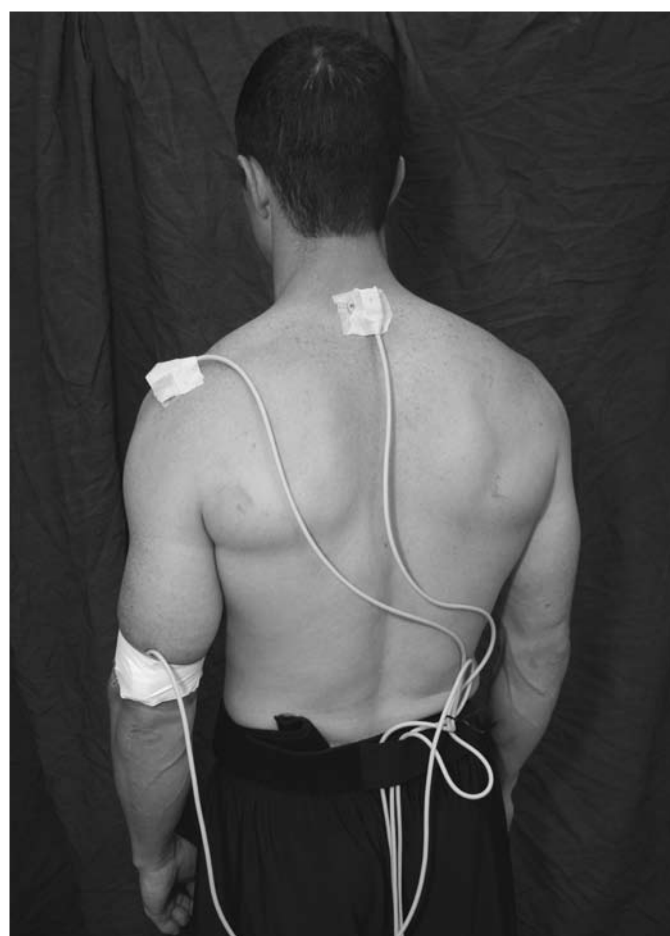

Figure 1. Position of electromagnetic motion sensors on the acromion, spine, and upper extremity.

the global reference system to local axes for each segment. The local axes all aligned with the reference axes of the electromagnetic tracking system to simplify data reduction.

A Chatillon CSD300 handheld dynamometer (Chatillon Force Measurement Systems, Largo, FL) was used to measure peak force output in pounds before and after the fatigue protocol. The dynamometer was calibrated for each testing session per the user manual.

Procedures

Electrode sites were prepared by shaving the participant's skin, if needed; lightly abrading the area; and cleaning it with isopropyl alcohol. A single reference electrode was placed over the clavicle of the dominant side. Two electrodes were placed in the primary fiber direction for each muscle in the following arrangement[15,16] (Figure 2): (1) serratus anterior, along the midaxillary line anterior to the latissimus dorsi muscle and lateral to the inferior angle of the scapula; (2) upper trapezius, midway between the spinous process of the seventh cervical vertebra and the posterior tip of the acromion process along the line of the trapezius muscle; (3) lower trapezius, obliquely upward and laterally along a line between the intersection of the spine of the scapula with the vertebral border of the scapula and the seventh thoracic spinous process; and (4) infraspinatus, midpoint and 2 fingerbreadths below and parallel to the scapular spine.

Separate maximal voluntary isometric contractions (MVICs) were performed using the handheld dynamometer for the upper trapezius, lower trapezius, serratus anterior, and infraspinatus muscles. The upper trapezius was assessed with the participant sitting while the shoulder was abducted to 90° with the neck bent to the side, rotated to the opposite side, and extended. Manual resistance at the head was directed toward the neutral position, and the handheld dynamometer was applied above the elbow with the force of the examiner (M.J.) in the direction of adduction.[17] For the lower trapezius, the participant lay prone with the arm in 125° of abduction in line with the lower trapezius fibers, and resistance was applied above the elbow perpendicular to the floor.[17] The serratus anterior was tested with the participant sitting and the shoulder abducted to 125° in the scapular plane. The handheld dynamometer was placed above the elbow, and manual resistance was applied at the inferior angle of the scapula in an attempt to derotate the scapula.[17] The infraspinatus muscle test involved shoulder external rotation at 90° of abduction with the participant lying prone. Resistance was applied toward internal rotation at the distal forearm. Blackburn et al[18] showed that this position was the most effective at activating the infraspinatus muscle.

During MVIC testing, participants were instructed to push with maximal effort against the handheld dynamometer for 5 seconds. Three MVICs were recorded for each muscle. Participants rested 30 seconds between trials for a given muscle and 1 minute between testing of different muscle groups. For each of the 3 trials performed per muscle, average EMG amplitude during the middle 1-second period was determined. This was averaged over the 3 trials and used to normalize EMG data collected during the prefatigue and postfatigue measurements. Thus, EMG data during prefatigue and postfatigue testing are expressed as a percentage of MVIC. An average of the 3 trials of peak force, which were calculated from the readings of the infraspinatus muscle test in pounds, also served as baseline peak force generated by the posterior cuff muscles and was used to define *fatigue*.

After MVIC testing, electromagnetic sensors were secured as described, and bony segments were digitized per the recommendations of the International Shoulder Group.[14] Participants

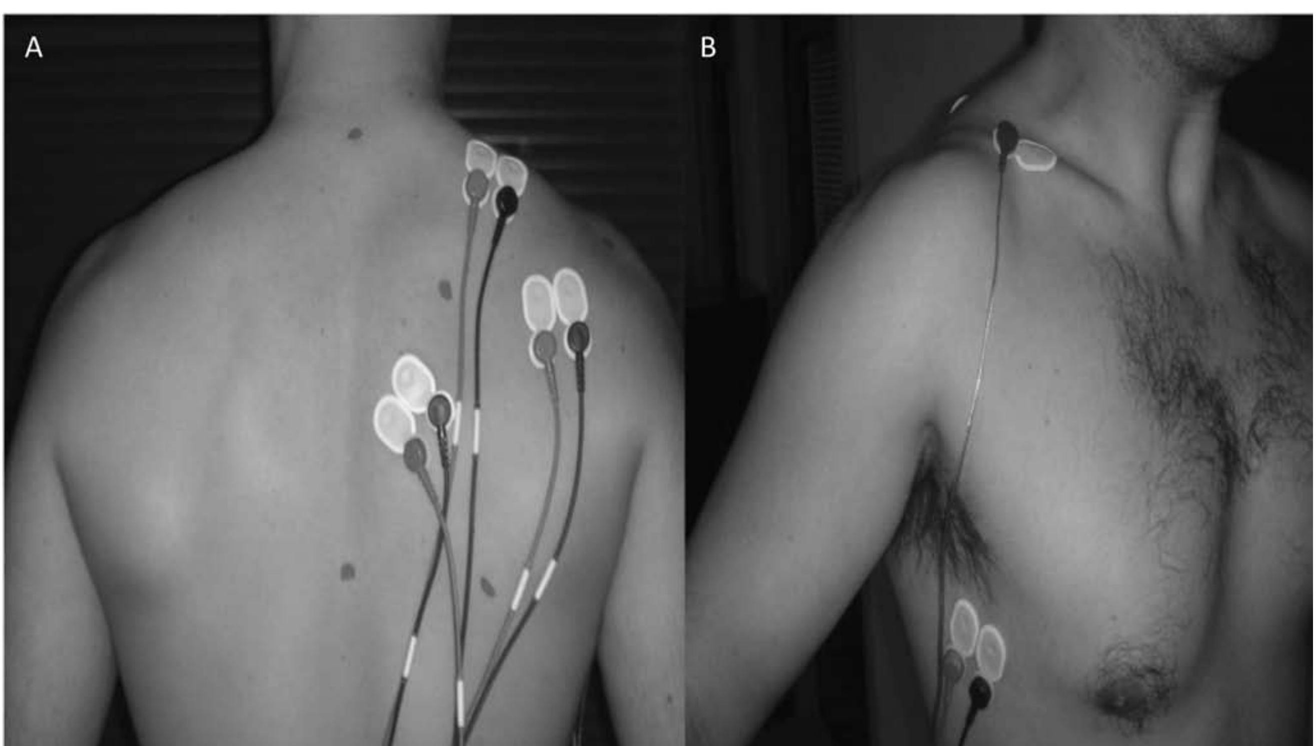

Figure 2. A and B, Surface electromyographic electrode placement for the upper trapezius, lower trapezius, serratus anterior, and infraspinatus muscles.

were seated with the trunk aligned vertically and the back supported. To minimize compensatory movement at the waist, a strap was used to stabilize the pelvis. This did not restrict scapular motion or interfere with the recording of muscle activity.

Participants were required to follow a diagonal path similar to a proprioceptive neuromuscular facilitation (PNF) upper extremity D2 pattern (Figure 3).[19] The motion involved flexion, abduction, and external rotation at the shoulder during humeral elevation (ascending phase) and involved shoulder extension, adduction, and internal rotation during humeral lowering (descending phase) with a dumbbell that was 25% of the baseline peak force generated during the infraspinatus muscle test. We used a weighted task to elicit greater changes in scapular motion.[4] In addition, pilot testing indicated that 25% of infraspinatus force was adequate to generate self-reported fatigue with repeated arm motion, and because infraspinatus fatigue was our primary interest, it was used to establish a baseline. During the motion, the elbow was maintained in extension. The path was outlined using an apparatus made from foam padding and polyvinyl chloride pipe, and it controlled for the path of humeral motion among participants and between prefatigue and postfatigue measurements. The height of the apparatus could be adjusted to ensure that all participants could move through the full ROM required by the path of motion of the apparatus. Participants were allowed to practice the diagonal pattern until they felt comfortable performing it.

Participants started with the upper extremity resting on a table, the palm facing inferiorly, and the thumb pointing directly posteriorly (humeral internal rotation). From this resting position, participants moved their upper extremities through the diagonal path with the load on a "ready-set-go" command. During the ascending phase, they were instructed to rotate their arms so their palms faced superiorly and their thumbs pointed directly posteriorly (humeral external rotation) at peak humeral elevation. During the descending phase, the motion was reversed and ended at the start position (Figure 3). A metronome set at 1 beat per second was used to keep the rate of motion constant. Participants were instructed to complete the ascending phase in 3 seconds, and they used the same amount of time for the descending phase. Each participant performed 5 trials, resting 3 seconds between trials. The EMG and 3-dimensional kinematic data were recorded continuously until participants had completed all 5 trials. After the fatigue protocol, the participants immediately (in less than 1 minute) repeated these test procedures.

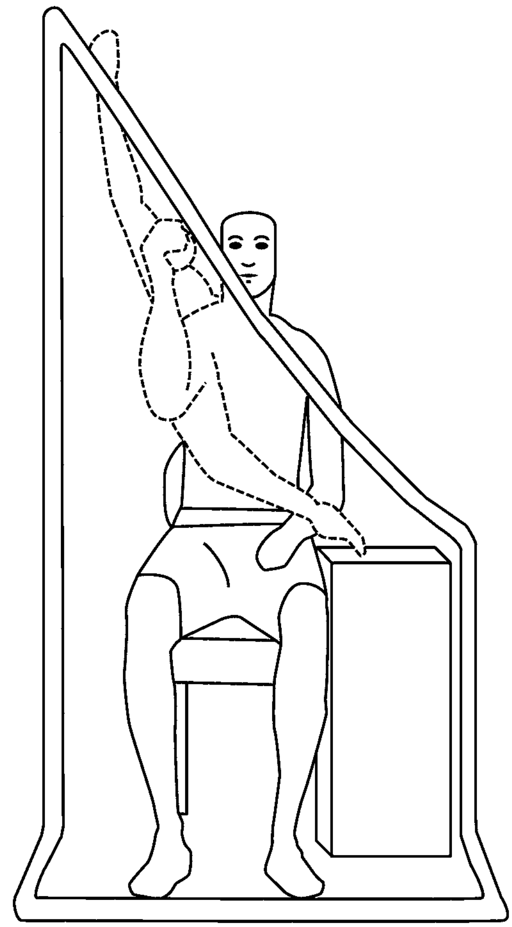

Figure 3. Diagonal movement pattern shows starting position (palm facing down, thumb pointing back) and peak humeral elevation (palm facing up, thumb pointing back).

Fatigue Protocol

For the fatigue protocol, participants lay prone on an adjustable table. The shoulder was positioned in 90° of abduction, and straps were used to stabilize the trunk and distal humerus. The fatiguing exercise involved shoulder external rotation through a range of 0° to 75° using the same dumbbell weight (25% of the baseline peak force generated during the infraspinatus muscle test) as the diagonal task (Figure 4). We kept the arc of motion consistent for participants by having bars that acted as markers at 0° and 75°. The rate of movement was kept constant across participants using a digital metronome; participants took 1 second to externally rotate from 0° to 75° and 1 second to return to the starting position. The exercise was stopped if the participant was unable to continue or could not keep pace with the metronome. At this point, the participant rested 30 seconds, and the exercise was repeated. This sequence of events continued until the participant completed a minimum of 5 sets and until the number of repetitions was less than 50% of the repetitions performed during the first set. At this point, we immediately reassessed humeral external rotation force production. Participants were considered fatigued only when average external rotation peak force decreased by more than 25% from baseline peak force.[6] Until this value was attained, participants continued the fatigue protocol with the dumbbell (Figure 5).

Data Reduction

The 3-dimensional coordinates of the digitized bony landmarks were calculated using The MotionMonitor software. Segment reference frames were defined according to the recommendations of the International Shoulder Group in 2002.[14] Humeral motions were calculated as the Euler angles of the humerus relative to the thorax reference frame in the following order of rotations: humeral internal-external rotation about the y′-axis, elevation about the x-axis, and internal-external rotation about the y″-axis. Scapula motions were calculated as the Euler angles of the scapula relative to the thorax reference frame in the following order of rotations: internal-external rotation about the y-axis, upward-downward rotation about the z-axis, and posterior-anterior tilting about the x-axis. Kinematic data were smoothed through a fourth-order, recursive, zero-

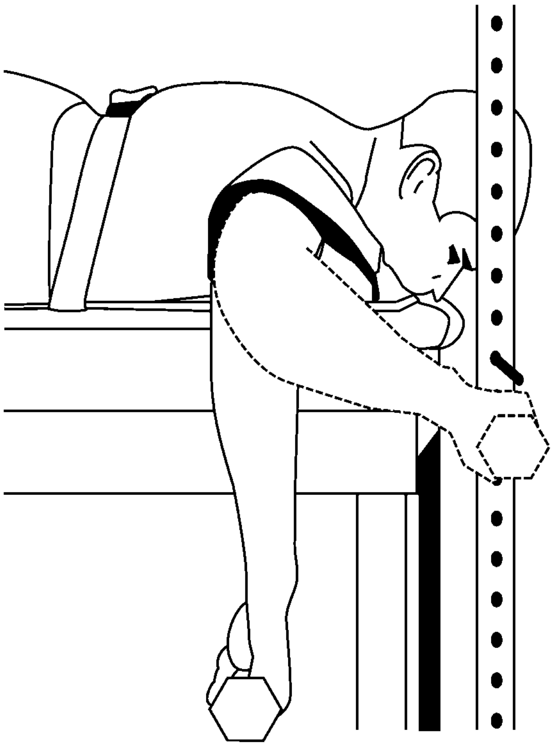

Figure 4. Fatiguing exercise involving 0° to 75° of external rotation at 90° of glenohumeral abduction.

phase-lag, low-pass digital Butterworth filter at an estimated optimal cutoff frequency of 3.5 Hz as determined by residual analysis of the signal.

The average scapulothoracic joint angle was calculated across the 5 trials before and after the fatigue protocol. Ascending ROM was calculated by subtracting the average starting joint angle from the average maximal joint angle during ascent. Descending ROM was calculated by subtracting the average ending joint angle from the average maximal joint angle during descent.

The EMG data were band-pass filtered (10–350 Hz) using a fourth-order, zero-phase-lag Butterworth filter. The EMG data were notch filtered at 60 Hz (1-Hz width). The root mean square of the EMG signal over a 20-millisecond time constant was taken. Average root mean square (ARMS) amplitude (percentage of MVIC) was the dependent variable assessed in the prefatigue and postfatigue states (independent variable). A baseline measure of resting muscle activity was assessed before testing began. We rested the participant's upper extremity on a table and recorded the EMG signal. The average ARMS over a 3-second window from this EMG data was used as an indicator of resting muscle activity.

Scapular kinematics and ARMS signal amplitude were calculated for the ascending and descending phases of the diagonal path. The *ascending phase* was defined as the phase from onset of humeral elevation to peak humeral elevation, and the *descending phase* was defined as the phase from peak humeral elevation until return to humeral elevation baseline position.

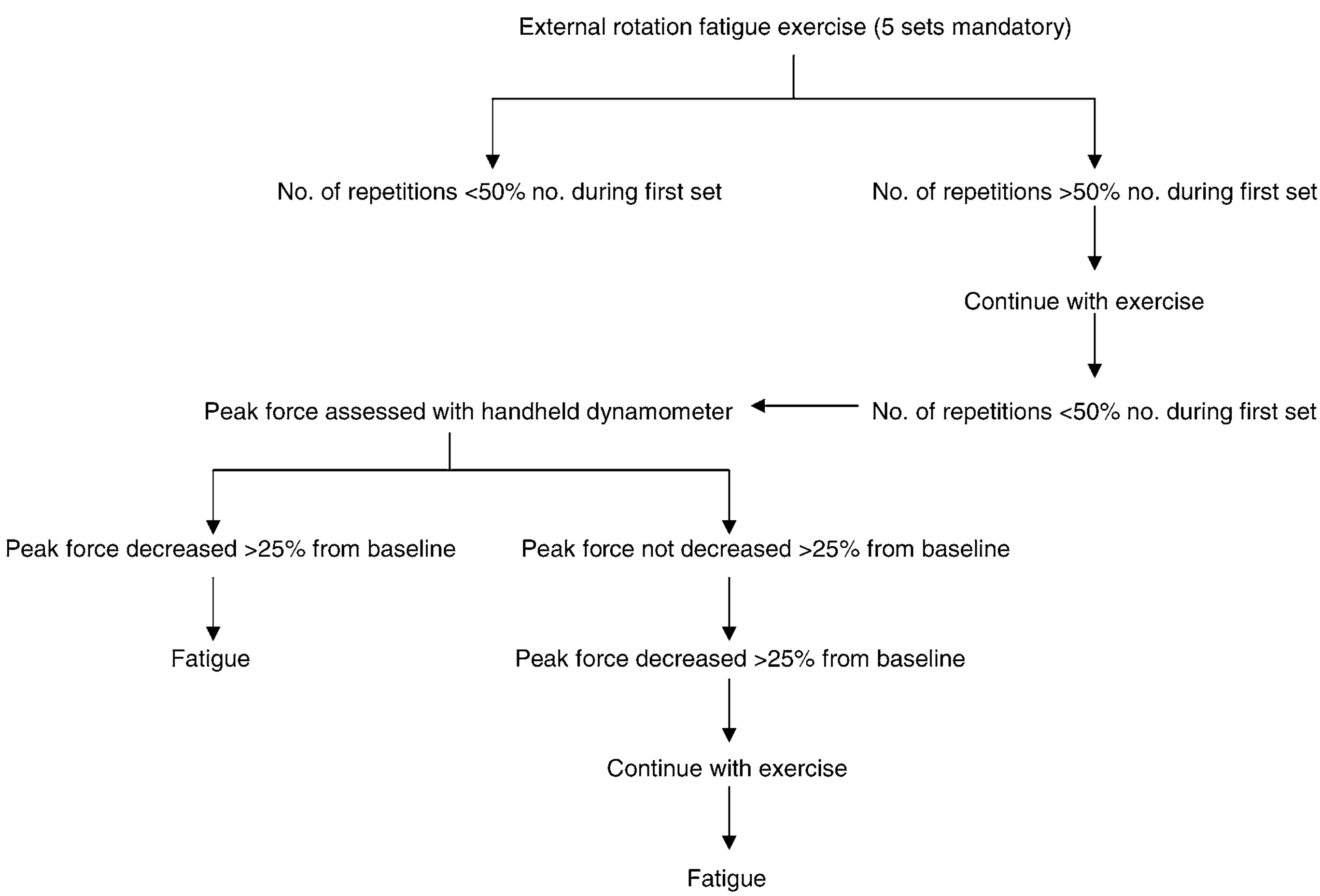

Figure 5. Flowchart summarizing the fatigue protocol.

Table 1. Percentage of Maximal Voluntary Isometric Contractions for the Upper Trapezius, Lower Trapezius, Serratus Anterior, and Infraspinatus in the Ascending and Descending Phases of the Prefatigue and Postfatigue Conditions (Mean [95% Confidence Interval])

	Ascending Phase		Descending Phase			
Muscle	Prefatigue, %	Postfatigue, %	Prefatigue, %	Postfatigue, %	Intraclass Correlation Coefficient (2,1)	Standard Error of Measurement, %
Upper trapezius	51 (43, 59)	51 (43, 59)	35 (29, 42)	34 (29, 42)	0.89	5.5
Lower trapezius	64 (52, 74)	50 (50, 69)	26 (21, 31)	24 (19, 28)	0.92	3.5
Serratus anterior	44 (33, 56)	43 (33, 54)	35 (25, 45)	35 (26, 45)	0.82	9.7
Infraspinatus	43 (34 ,57)	44 (35, 53)	29[a] (23, 37)	33[a] (25, 41)	0.88	3.2

[a] Indicates that the percentage of maximal voluntary isometric contractions for the infraspinatus increased during the descending phase of the diagonal task from prefatigue to postfatigue ($P<.05$).

The average value of the 5 trials was taken and used for data analysis for each dependent variable. Each of the scapular kinematic and EMG variables demonstrated acceptable intrasession reliability and demonstrated precision as indicated by intraclass correlation coefficient (ICC [2,1]) and standard error of measurement values (Table 1).

Data Analysis

Separate repeated-measures analyses of variance (condition [prefatigue, postfatigue]×phase [ascending, descending]) were performed to compare scapular ROM for upward-downward rotation, internal-external rotation, and anterior-posterior tilting and to compare ARMS amplitude for the upper trapezius, lower trapezius, serratus anterior, and infraspinatus. We used a Pearson product moment correlation to confirm any relationships between individual muscle activities. Interactions were analyzed using the Tukey HSD test. The α level was set a priori at .05. All data were analyzed using SPSS (version 12.0; SPSS Inc, Chicago, IL).

RESULTS

Scapular Upward-Downward Rotation

We found a phase×condition interaction effect for scapular upward-downward rotation ROM ($F_{1,24}=3.7$, $P=.04$, effect size [ES]=0.9). Post hoc analysis revealed that scapular upward rotation during the ascending phase was greater at postfatigue than prefatigue (Figure 6).

Scapular Internal-External Rotation

We found no main effects ($F_{1,24}=0.35$, $P=.88$, ES=0.04, $1-ß=0.05$) or interaction effects ($F_{1,24}=0.23$, $P=.81$, ES=0.04, $1-ß=0.04$) involving condition for scapular internal-external rotation ROM, indicating that no differences existed in scapular internal-external rotation motion prefatigue or postfatigue.

Scapular Anterior-Posterior Tilting

We found no main effect ($F_{1,24}=1.66$, $P=.11$, ES=0.35, $1-ß=0.32$) or interaction effects ($F_{1,24}=1.94$, $P=.66$, ES=0.41, $1-ß=0.38$) involving condition for scapular anterior-posterior tilting ROM, indicating that no differences existed in scapular anterior-posterior tilting motion prefatigue or postfatigue.

ARMS Amplitude

We found a main effect for condition for the lower trapezius ARMS amplitude ($F_{1,25}=5.098$, $P=.03$, ES=0.9), showing decreased lower trapezius activity after the fatigue protocol in the ascending and descending phases of the diagonal task (Table 2). We also found a phase×condition interaction effect for the infraspinatus ARMS amplitude ($F_{1,25}=5.534$, $P=.03$, ES=1.0) (Table 1). Post hoc analysis indicated increased infraspinatus activation in the descending phase of the diagonal task. A Pearson product moment correlation coefficient revealed that increases in infraspinatus activity tended to occur with decreases in lower trapezius activity ($r=-0.43$, $P=.04$).

We did not find a main effect involving condition for the upper trapezius ($F_{1,25}=0.185$, $P=.67$, ES=0.15, $1-\beta=0.070$), serratus anterior ($F_{1,25}=0.036$, $P=.85$, ES=0.04, $1-\beta=0.054$), or infraspinatus ($F_{1,25}=1.677$, $P=.21$, ES=0.45, $1-\beta=0.238$). We did not find interaction effects for the upper trapezius ($F_{1,25}=0.266$, $P=.61$, $1-\beta=0.079$), lower trapezius ($F_{1,25}=1.562$, $P=.22$, $1-\beta=0.224$), or serratus anterior ($F_{1,25}=4.047$, $P=.06$, $1-\beta=0.488$). These results suggested that upper trapezius and serratus anterior ARMS amplitudes were not affected by the fatigue protocol (Table 1).

DISCUSSION

Our results showed that shoulder external rotation muscle fatigue contributed to altered scapular muscle activation and kinematics. The most important findings of this study were the changes observed in lower trapezius activation (4% decrease), infraspinatus activity (4% increase in the descending phase), and scapular upward rotation ROM (3° increase) from prefatigue to postfatigue.

Descending-phase infraspinatus activity increased by 4%, whereas lower trapezius activation decreased by 4% postfatigue. We believe these alterations are partly the result of not controlling scapular position during shoulder external rotation at 90° of glenohumeral abduction. Recently, researchers have shown that this position facilitates greater activation of the lower trapezius than of the infraspinatus.[18,19,20] During this task, the lower trapezius should function isometrically to stabilize the scapula on the thorax, and such a prolonged contraction might have contributed to lower trapezius fatigue. The lower trapezius fatigue might alter scapular position and affect the length-tension relationship for the infraspinatus. Thus, the concurrent increase in infraspinatus activity that we observed might have

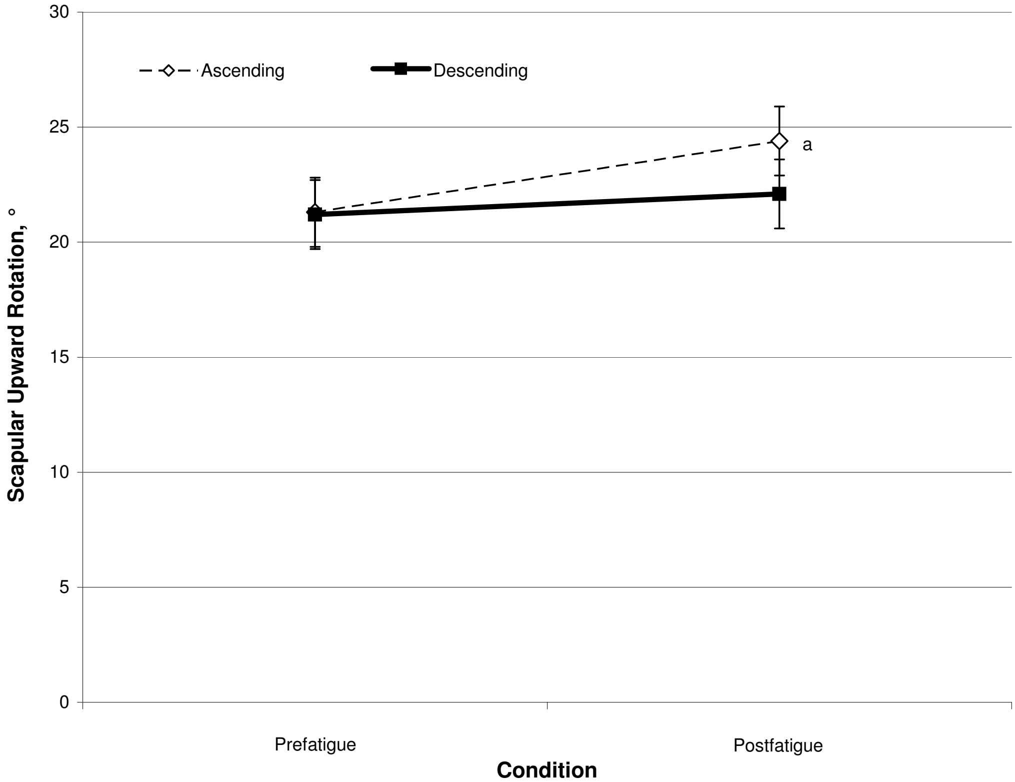

Figure 6. Scapular upward rotation angles in the ascending and descending phases. [a] Indicates a difference between the prefatigue and postfatigue states. Error bars represent 1 SD about the mean.

been a compensatory mechanism to maintain force production despite altered scapular position. We performed a secondary analysis to confirm this relationship between infraspinatus and lower trapezius muscle activity using a Pearson product moment correlation coefficient. As suggested by the initial analysis, increases in infraspinatus activity tended to occur with decreases in lower trapezius activity ($r = -0.43$, $P = .04$). Other investigators[21–23] also have illustrated similar decreases in rotator cuff performance with altered scapular position. The increase in infraspinatus activity also might have resulted from the indirect effect of altered lower trapezius activity on the glenohumeral joint. The lower trapezius has been shown to be important in maintaining the scapula's axis of rotation.[7,24–26] With altered lower trapezius activation, an unstable scapular base might affect the center of rotation of the glenohumeral joint and alter length-tension relations for surrounding muscles, such as the infraspinatus. However, increased infraspinatus activity was observed only in the descending phase despite decreased lower trapezius activity through both phases postfatigue. Altered activation in other untested muscles, such as the teres minor, rhomboids, and levator scapulae, might have played a role.

The upper trapezius and serratus anterior did not show a change in activation postfatigue. The fatigue protocol might not have fatigued these muscles and therefore did not affect their activation patterns.

The changes in infraspinatus and lower trapezius activity observed were contrary to what we expected and also were not consistent with findings by Ebaugh et al,[3] who reported an increase in lower trapezius activity and a decrease in infraspinatus activity after an external rotation task. These differences might be explained in part by methods used to fatigue the external rotator muscles and criteria used to define *fatigue*. Ebaugh et al[3] used static and dynamic external rotation at 10° to 20° of glenohumeral abduction; we attempted to fatigue shoulder external rotation muscles at 90° of glenohumeral abduction. The 2 studies also differ in terms of the movement used to assess muscle activation prefatigue and postfatigue. Ebaugh et al[3] used a single-plane motion (scapular-plane arm elevation), whereas we used a multiplanar motion similar to a PNF D2 pattern. This diagonal motion might have contributed to the differential activation seen in the periscapular muscles. The upper extremity tested also was different in the 2 studies. Ebaugh et al[3] used the dominant and nondominant sides; we tested only the dominant shoulder. Yoshizaki et al[27] showed dissimilar shoulder muscle activation between dominant and nondominant shoulders, and this might explain, in part, the differences observed.

Table 2. Percentage of Maximal Voluntary Isometric Contractions for the Upper Trapezius, Lower Trapezius, Serratus Anterior, and Infraspinatus in the Prefatigue and Postfatigue Conditions (Mean [95% Confidence Interval])

	Condition	
Muscle	Prefatigue, %	Postfatigue, %
Upper trapezius	43 (36, 50)	43 (36, 49)
Lower trapezius	45[a] (38, 52)	41[a] (36, 48)
Serratus anterior	40 (29, 50)	39 (29, 49)
Infraspinatus	37 (29, 45)	39 (30, 47)

[a] Indicates that the percentage of maximal voluntary isometric contractions for the lower trapezius decreased during the diagonal task from prefatigue to postfatigue ($P < .05$).

A 3° or 12% increase (large ES of 0.9) in ascending-phase scapular upward rotation motion was noted between the prefatigue and postfatigue measurements. We believe that although the change appears small, it might be clinically important, considering that the average normal height of the subacromial space is only 9 to 10 mm.[28] Our finding of increased scapular upward rotation ROM is in agreement with that of Ebaugh et al.[3] However, Tsai et al[6] reported decreases in scapular upward rotation motion postfatigue. The increase in upward rotation motion we observed is surprising given the decrease in lower trapezius activation. Previous researchers[29] who used bone pins have shown clavicular elevation (translation) to occur concurrent with scapular upward rotation. This finding might explain the increases in scapular upward rotation range, but we did not assess this motion. Another possibility is that the increase in scapular upward rotation ROM might reflect a compensatory mechanism by which the fatigued shoulder maintains a normal subacromial space via altered activation in other shoulder muscles (levator scapulae, rhomboids, latissimus dorsi) that we did not test. The conflicting evidence on scapular upward rotation motion among studies makes it difficult to hypothesize the effect of altered position on subacromial volume. The inconsistency might result from differences in upper extremity tested (dominant versus nondominant), fatigue protocol, and movement task among studies. Similar unexpected findings suggested that scapular upward rotation motion is variable and warrants closer investigation.[30]

No differences were observed in scapular posterior tilting or external rotation ROM postfatigue. These findings were not in agreement with those of Ebaugh et al[3] and Tsai et al.[6] Ebaugh et al[3] reported a decrease in scapular posterior tilting motion and a trend toward increased scapular external rotation motion postfatigue, whereas Tsai et al[6] found decreased posterior tilting and external rotation ROM. The unexpected absence of changes in posterior tilting and external rotation motion might be due to the functional movement pattern used. Recently, researchers[30,31] have shown that observed differences and total ROM of scapular internal-external rotation and anterior-posterior tilting during scapular-plane elevation are not as large as elevation during flexion and abduction-plane tasks. Differences in methods or fatigue protocols among the 3 studies might also contribute to the observed discrepancies.

We believe these results have important clinical implications for overhead athletes who experience shoulder girdle fatigue because they provide a potential injury mechanism for rotator cuff strains commonly seen in these athletes. Our results suggest that the force couple between the lower trapezius and infraspinatus is altered with shoulder external rotation muscle fatigue. This might impair the ability of the overhead athlete to adequately stabilize the scapula and humeral head. Considering the repetitive nature of overhead sports, chronically increased infraspinatus activity also might place greater stress on its tendon and predispose it to early failure. Thus, our results highlight the interdependence among the infraspinatus, a rotator cuff muscle, and the lower trapezius, a scapular stabilizer, during overhead activity. Clinicians should consider this relationship when selecting shoulder exercises for overhead athletes.

Limitations

We acknowledge some limitations to the study. Our participant sample included young intercollegiate or collegiate club overhead athletes without a history of shoulder conditions or recent shoulder pain. This sample should be kept in mind when interpreting our results and comparing them with the results of other studies.

In screening appropriate participants for the study, we did not examine them for scapular dyskinesis. Not controlling for scapular position during the fatiguing exercise might have contributed to alterations in muscle activity observed postfatigue. Participants also were instructed not to participate in any fatiguing exercises of the shoulder at least 12 hours before testing. Because delayed-onset muscle soreness has been reported to peak 24 to 48 hours after activity, some of our participants might have been experiencing fatigue before testing.

During pilot testing, some participants had difficulty attaining 90° of external rotation from a prone position. Participants differed in their total rotation range at the glenohumeral joint. However, all of them were able to achieve 75° of prone external rotation. Therefore, we decided to use a 0° to 75° range to keep the motion consistent among participants. We realize that this might be a limitation to our study because muscle activation in participants might differ depending on what part of their maximal range they are working.

Limitations common to the use of surface electromyography must be noted. We assumed the signal was representative of the whole muscle or muscle group of interest. Potential alterations in the signal might have existed due to muscle movement below the electrode and crosstalk from nearby muscles, such as the rhomboids and latissimus dorsi. We tried to minimize this by normalizing the EMG data. Our EMG analysis was limited to the upper trapezius, lower trapezius, serratus anterior, and infraspinatus muscles. No data were collected from other scapulothoracic or glenohumeral muscles, such as the teres minor, that might impart forces to the scapula. The amount of glenohumeral abduction used for the external rotation muscle fatigue might have activated the teres minor to a greater extent, which might partially explain the increased infraspinatus activity as an adaptive mechanism.

The kinetic chain was not allowed to operate in our study because the participants were seated during testing and prone during the fatigue protocol. This positioning might have affected torques generated about the shoulder. In addition, the motion used for the fatigue protocol was uniplanar, which might not have been a functional fatiguing position in our population. In addition, a PNF D2 pattern–like movement was chosen for testing because of its resemblance to overhead activities. We realize that differences exist between this motion and the actual motions performed by overhead athletes during training or competition.

Only 2 other research groups[3,6] have studied the effects of shoulder external rotation muscle fatigue on scapular muscle activation and kinematics. Limited comparisons can be made with these studies because of differences in methods and fatigue protocol. Therefore, our explanations of the findings observed can be regarded only as hypotheses based on the studies in which researchers investigated fatigue-induced kinematic changes about the shoulder and on studies in which researchers compared activation differences between healthy and symptomatic shoulders.

Clinical Implications

The results of our study have relevance for shoulder rehabilitation and injury-prevention programs. Fatigue induced through repeated overhead glenohumeral external rotation resulted in altered activation in the lower trapezius and infraspinatus muscles and in increased scapular upward rotation motion. Such scapular activation and kinematic changes have been linked to many injuries, including subacromial impingement, rotator cuff tears, and glenohumeral instability.[32–35] Addressing these imbalances through appropriate exercises is imperative for establishing normal shoulder function.

CONCLUSIONS

We highlighted the importance of shoulder force couples and their influence on kinematics. We also emphasized the interdependence between the infraspinatus and lower trapezius muscles. Future research in muscle activation and scapular kinematic changes after the shoulder is fatigued in a more functional manner, such as throwing a baseball or spiking a volleyball, is warranted.

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